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A Study of the Relationship of the Proctor Optimum Moisture Content and the Full Saturation Line for Granular 'A' Aggregates

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SUMMARY

One of the problems with the compaction of Granular 'A' materials in the field is the control of optimum moisture content. Usually, laboratory testing has been carried out to determine maximum wet density, maximum dry density and optimum moisture content for the material to be used. Since free water is usually encountered in the laboratory test, the values of optimum moisture content determined may be erroneous. It also follows that the maximum dry density used for acceptance of compaction may also be incorrect.

A fairly simple test program was carried out on four Granular 'A' materials to investigate this and recommendations made for a modification to the laboratory procedure for these materials.

INTRODUCTION

It has been recognized for some time that the standard Proctor test (M.T.C. Method LS-706), when performed on relatively free-draining aggregates such as Granular 'A', will not produce a well-defined moisture-density curve. Thus, the values obtained for optimum moisture content and maximum dry density may be unreliable. The indications are that the optimum moisture content reaches or exceeds the zero air void line, which is, of course, totally wrong.

Since the relative density of aggregates prior to a Proctor test is not routinely measured, the location of the full saturation line on the Proctor graph is not known. Due to the lack of knowledge of this limiting moisture line, there is a possibility that the recommendations of optimum moisture content made for field compaction of granular materials may be as much as 2% too high.

THE COMPACTION TEST

The laboratory compaction testing of materials containing a fairly high percentage of coarse material (up to 37.5 mm) is carried out using M.T.C. Test Method LS-706, procedure 3. This procedure designates the use of a 152.4 mm diameter mold with material passing the 26.5 mm sieve. Any 'oversize' material is generally replaced by an equal amount of pass 26.5 mm, retained 4.75 mm material, with a grading equivalent to the original sample. It is desirable to carry out at least five trials to produce an acceptable compaction curve. The idealized curve should consist of two points of increasing density, one point at or near the optimum moisture content, and two points of decreasing density, all with increasing moisture content.

In practice, this idealized concept is difficult to realize with granular materials for the following reasons:

1) No drop in density. This is a common phenomenon with the materials under consideration. Since they are relatively free-draining, a point is reached during the test at which 'free water' appears. This is generally squeezed out at the base of the mold and must be removed prior to determination of the total mass. Successive determinations produce an increase in density with little further increase in water content.

2) Inconsistent gradation. Since the test sample contains a wide variation in grain sizes, it is difficult to ensure that separate test runs will contain the same proportions of individual particle sizes.

3) Inconsistent volume determination. It is very difficult to 'strike off' the surface of the compacted material with any degree of consistency because of the coarse particles present. Usually a judgement has to be made that the volume of the aggregate projecting above the surface is equal to the volume of the voids or depressions in the surface.

4) Inconsistent moisture determination. After compaction, the sample is transferred from the mold to the mixing bowl and a moisture sample taken. Since the material is free-draining, the water

tends to migrate to the bottom of the bowl, making the selection of a "representative" moisture sample difficult.

An element of soil contains many shapes and sizes of particles, which do not fill all of the space occupied by the element. The voids between the particles may be filled with water (saturated soil), air (dry soil) or a mixture of air and water. The latter is generally referred to as 'multiphase' system - solid (mineral particles), liquid (water) and gas (air).

If the soil is compacted, and the dry bulk density increases, the compacting force must overcome the frictional properties of the soil particles. The addition of water acts as 'lubrication', and higher values of dry bulk density will result. This effect continues with increasing moisture content until there is just sufficient water to fill the voids. At this point, the voids in the soil are at a minimum and the dry bulk density at a maximum. A further addition of water causes re-arrangement of the particles, an increase in voids and a resulting decrease in dry bulk density. Therefore, for any given soil and compaction process, an optimum moisture content may be determined at which the dry density is a maximum. A relationship may be developed from the values of moisture content, dry density and relative density obtained for any soil. This relationship gives a graphical construction known as the full saturation line or zero air voids line. The relationship is as follows:

$$\rho_d = \frac{\rho_w}{\frac{1}{D_R} + \frac{w}{100}}$$

where ρ_d = dry density t/m^3
ρ_w = density of water t/m^3
D_R = relative density
w = water content

It has been demonstrated by the analysis of test data that the dry density curves for granular materials frequently cross the full saturation line and this is shown in Figure 1.

A value of 2.71 was used for the relative density in the calculation of the full saturation line. This was a mean of a number of determinations made on samples of crushed gravel from southern Ontario.

TEST PROGRAM

A. Investigation

In order to investigate moisture and density values above the full saturation line, it was decided to carry out a laboratory testing program using four Granular 'A' materials. Two of these were crushed gravel from Armbro-Caledon and Hancock Sand & Gravel. The grain size curves are shown in Figure 2. The other two samples were quarried materials from Milton and Lincoln quarries. Grain size curves are shown in Figure 3. Sufficient material was collected for each sample to allow the preparation of at least twelve 9 kg Proctor test specimens.

Each material was graded, the stone being kept in separate sizes and the sand re-bagged. The test program was as follows:

1) Prepare duplicate sand and stone relative density tests on each material.

2) Prepare four separate Proctor samples to each of three gradations - fine, median and coarse. The fine gradation conformed to the upper limit of the Granular 'A' specification band. The coarse gradation conformed to the lower limit and the median gradation selected in between the two limits. These gradations are shown in Figure 4.

3) Carry out regular Proctor tests on two samples from each set of four for each gradation.

4) Carry out compaction tests on the other two samples of each set of four using a sealed-base Proctor mold and starting each test at a water content of C. Water to be added in 1% increments and behaviour at or near the saturation line observed.

5) Compute the full saturation line for each material using a mean of the relative density determinations on the sand and gravel portions of each of the four materials.

6) Use the mechanical compaction device for all tests to eliminate variations in compactive effort as far as possible.

B. Test Results

1) Armbro-Caledon Material. The maximum dry density and optimum moisture contents are presented in Table 1.

Gradation		Unsealed Mold		Sealed Mold	
		1	2	1	2
Coarse	ρ_d	2.314	2.290	2.320	--
	w_{opt}	6.3	7.1	5.6	--
Median	ρ_d	2.324	2.330	2.246	2.248
	w_{opt}	6.0	5.9	5.8	5.9
Fine	ρ_d	2.294	2.286	2.226	2.215
	w_{opt}	6.4	6.0	6.5	6.8

Note: ρ_d in t/m^3 and w_{opt} in %.

TABLE 1 ARMBRO-CALEDON MATERIAL

Figure 5 shows the comparison between tests on the three selected gradations in the unsealed mold. Free water was observed on the third or fourth run for each test.

Figure 6 shows similar data using the sealed mold and carrying out the moisture content on the entire sample for each run.

A value for the relative density of 2.715 was used to calculate the data for the full saturation line. This was obtained by carrying out relative density tests on the fine and coarse aggregate by test methods LS-604 and LS-605.

2) Hancock S & G Material. The maximum dry density and optimum moisture contents are presented in Table 2.

Gradation		Unsealed Mold		Sealed Mold	
		1	2	1	2
Coarse	ρ_d	2.393	2.431	2.355	2.342
	w_{opt}	4.8	5.3	5.1	5.4
Median	ρ_d	2.366	2.410	2.320	2.295
	w_{opt}	5.1	4.4	5.2	6.3
Fine	ρ_d	2.320	2.265	2.269	2.279
	w_{opt}	6.2	6.1	5.9	6.3

Note: ρ_d in t/m^3 and w_{opt} in %.

TABLE 2 HANCOCK S & G MATERIAL

Figure 7 shows the comparison between tests on the three selected gradations in the unsealed mold. Free water was observed only on one run of the coarse gradation.

Figure 8 shows similar data using the sealed mold and carrying out the moisture content on the entire sample for each run.

The same value of relative density was found for this material and used to draw the full saturation line.

3) Milton Quarry Material. The maximum dry density and optimum moisture contents are presented in Table 3.

Gradation		Unsealed Mold		Sealed Mold	
		1	2	1	2
Coarse	ρ_d	2.322	2.333	2.370	2.334
	w_{opt}	7.1	6.9	5.9	6.1
Median	ρ_d	2.307	2.246	2.334	2.291
	w_{opt}	7.7	7.8	6.4	7.2
Fine	ρ_d	2.302	2.288	2.298	2.303
	w_{opt}	7.7	7.3	7.0	6.8

Note: ρ_d in t/m^3 and w_{opt} in %.

TABLE 3 MILTON QUARRY MATERIAL

Figure 9 shows the unsealed mold tests. Free water was observed in fairly large amounts on run five of the majority of the tests.

Figure 10 shows similar data using the unsealed mold with moisture content determinations on a total sample basis. The relative density used to calculate the saturation line was 2.796, somewhat higher than the pit run materials.

4) Lincoln Quarry Material. The maximum dry density and optimum moisture contents are presented in Table 4.

Gradation		Unsealed Mold		Sealed Mold	
		1	2	1	2
Coarse	ρ_d	2.294	2.236	2.284	2.292
	w_{opt}	7.4	7.3	6.8	6.7
Median	ρ_d	2.266	2.295	2.290	2.302
	w_{opt}	7.9	7.4	6.9	7.0
Fine	ρ_d	2.264	2.263	2.271	2.282
	w_{opt}	8.3	7.4	7.3	7.3

Note: ρ_d in t/m^3 and w_{opt} in %.

TABLE 4 LINCOLN QUARRY MATERIAL

Figures 11 and 12 show similar data to the previous materials. The relative density used to calculate the saturation line was 2.790.

C. Discussion of Test Results

It has been reported by other authorities that considerable differences may occur in the values of dry density found for a material from a single source. Differences between individual samples up to 0.16 t/m^3 (10 p.c.f.) have been reported. These differences are largely due to variation in gradation, and this is supported by the current study. Variations in dry density from 0.2 to 0.166 t/m^3 (1.25 to 10.36 p.c.f.) were found.

Variations in dry density between individual samples of the same gradation have also been reported, and in the present study these averaged 0.029 t/m^3 (1.81 p.c.f.) for tests carried out in the unsealed mold. However, the tests carried out in the sealed mold gave typically lower differences, {0.015 t/m^3 (0.9 p.c.f.)}, some 50% less than for the unsealed mold.

There appeared to be little difference in optimum moisture content between tests carried out in unsealed and sealed molds for the crushed gravel materials. However, the optimum moisture content for the quarried materials was generally lower by 0.5-1% for tests carried out in the sealed mold.

The curves of dry density vs. moisture content for tests carried out in the unsealed molds all cross or approach very closely the zero air voids line (See Figures 5, 7, 9 and 11). This, as has previously been stated, is not theoretically possible. In addition, there is very little pattern between the curves for coarse, median and fine gradations.

The curves for the tests carried out in the sealed mold were significantly better. None of the curves crossed the zero air voids line, and there was a definite pattern to the curves. This was very logical, with the maximum dry density decreasing from the coarse to fine gradation for each material tested. Of greater significance was the fact that the density points wet of optimum moisture content decreased along a line representing approximately 1½% air voids. This was applicable to three of the materials tested, the only exception being the material from Milton Quarry, where the density points followed a line of approximately 0.5% air voids.

Observation of the curves produced from tests in the sealed mold show dry densities that are generally higher at a moisture content of 0 than 2%. This is a typical phenomenon, and the shape of the initial part of the curve is representative of the type of material under test, 'rounded' materials producing a smooth inverse loop and 'angular' producing a stepped appearance.

It should be noted that the maximum dry densities obtained in the sealed mold are generally lower than those obtained in the unsealed mold. This is a significant factor in keeping the dry density curve on the dry side of the zero air voids line.

CONCLUSIONS

A number of conclusions may be drawn from the limited testing program carried out.

1. Results obtained for the maximum dry density using the standard test procedure are subject to fairly wide variation.
2. Although the optimum moisture content values obtained using the standard test procedure appear reasonable, the combination of maximum dry density and optimum moisture content obtained causes the results to cross the zero air voids line.
3. Using a sealed base Proctor mold to avoid the free water condition improves the controllability of the test and appears to give lower values of dry density.
4. Use of the total sample for moisture determination is far more accurate than the standard test procedure.

It is obviously not practical to use a sealed base Proctor mold in the test procedure on a day to day basis and use the total sample for a moisture content determination. This would mean that a single test would take approximately four days. The sealed base mold could be used if the current method of taking the moisture content sample is used. However, as pointed out earlier, this leads to inconsistencies in moisture determination.

It would be feasible to use in the laboratory an expansion of the one point Proctor method. This would necessitate drawing the line of zero air voids on the compaction chart. A number of density and moisture determinations would then be made using the standard technique, but stopping just short of a density drop, or free water appearing at the base of the mold. The points obtained would be plotted on the graph, and the final curve drawn to fall on the dry side of, and parallel to, the zero air voids line. This is shown in Figure 13.

In order to facilitate drawing the zero air voids line, a table of dry density values has been prepared. These correspond to various

moisture contents for different values of relative density, and are shown in Table 5.

If relative density values have been obtained for the material the use of the table is simple. If not, an assumption may be made that values of relative density will be approximately 2.72 for pit-run materials and 2.79 for quarried materials. These values apply to materials in the Toronto area, and may vary in other parts of the Province.

RECOMMENDATIONS

1. The current laboratory test procedure for compaction testing of granular materials frequently leads to values of optimum moisture content and maximum dry density that are too high.

   IT IS RECOMMENDED THAT THE ZERO AIR VOID LINE BE USED AS A GUIDE WHEN PERFORMING THE TEST. THE PROCEDURE IS OUTLINED ON PAGE 9 OF THIS REPORT. FROM THE RESULTS OF THIS STUDY, 1½% AIR VOIDS APPEARS TO BE INDICATIVE OF THE PROBABLE DOWNSLOPE OF THE PROCTOR CURVE.

2. Values of relative density are required for materials tested in order to accurately construct the zero air void line.

   IT IS RECOMMENDED THAT RELATIVE DENSITY MEASUREMENTS BE MADE ON GRANULAR MATERIALS SUBMITTED FOR COMPACTION TESTING IN ORDER TO CONSTRUCT THE ZERO AIR VOID LINE. IF THIS IS NOT PRACTICAL, VALUES SUCH AS THOSE LISTED IN TABLE 1 SHOULD BE USED. VALUES OF 2.71 FOR CRUSHED GRAVEL AND 2.79 FOR QUARRIED MATERIAL HAVE ALREADY BEEN DETERMINED FOR THIS REPORT. THESE MAY BE USED AS A GUIDE.

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BARSVARY, A. K. and KORGEMAGI, P; 1979; *The Variability of Laboratory Proctor Density Tests;* M.T.C. Report EM-32.

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M.T.C. LS 604; 1979; *Method of Test for Relative Density and Absorption of Coarse Aggregate;* M.T.C. Laboratory Testing Manual, 1979.

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M.T.C. LS 706; 1979; *Method of Test for Moisture-Density Relationship of Soils;* M.T.C. Laboratory Testing Manual, 1979.

NIELSON, G.F.; *Characteristics of Compacted Bases and Subbases;* Utah State Highway Dept., Project #HPR-1(5), 1967.

ROSTON, J. P., ROBERTS, F. L., and BARON, W.; *Density Standards for Field Compaction of Granular Bases and Subbases;* National Cooperative Highway Research Program Report 172, Washington, DC, 1976.

ACKNOWLEDGEMENTS

Many people have provided valuable assistance in the preparation of this report. The help and co-operation of these people is gratefully acknowledged.

The staff of the Preparation Laboratory for the collection and initial preparation of the materials used. Mr. John Smith of the Soils & Aggregates Section for his painstaking performance of the testing program. Miss Joanne Hirons of the Soils & Aggregates Section for the typing and preparation of tables.

APPENDIX I

FIGURES

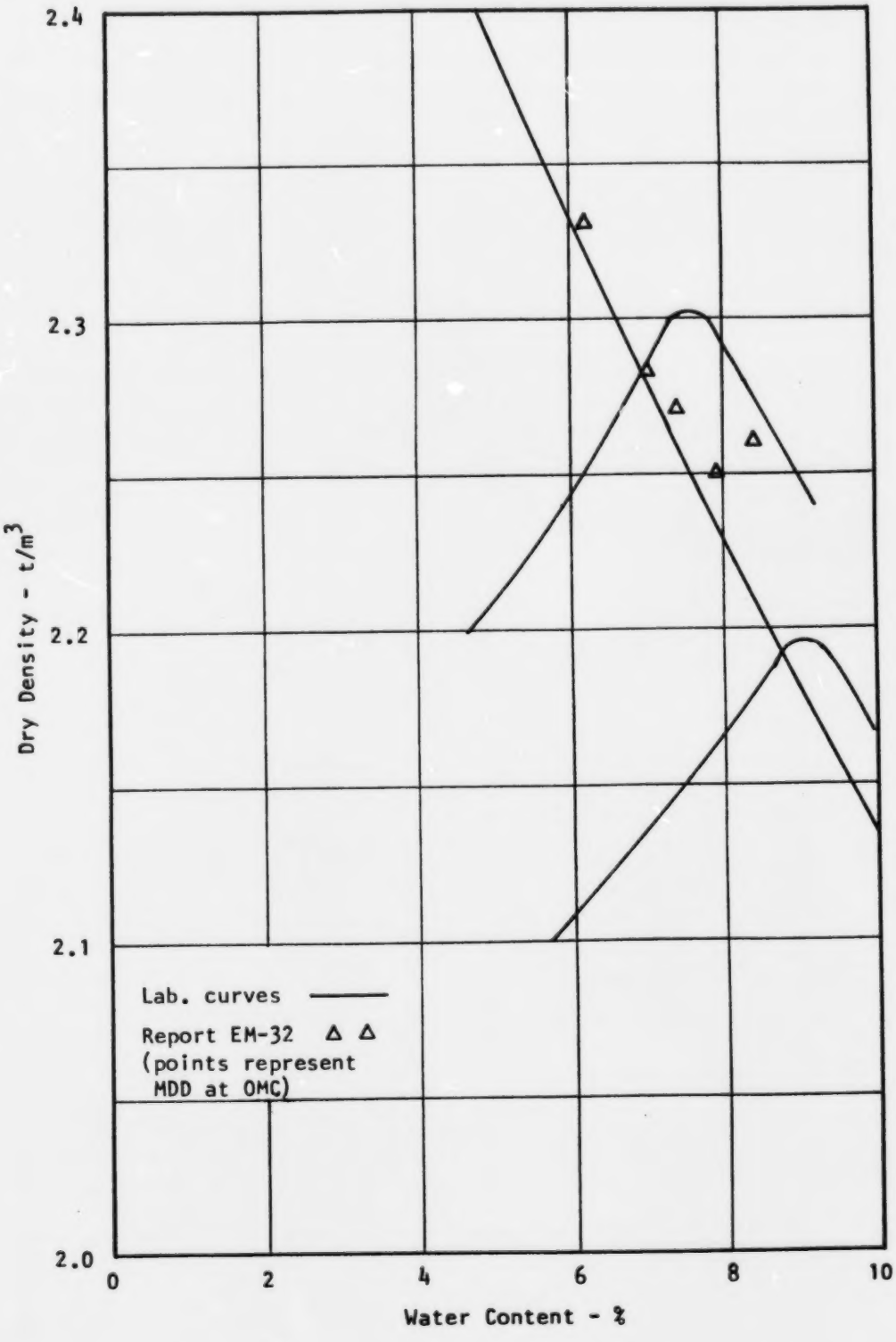

Figure 1. Dry density points wet of saturation line.

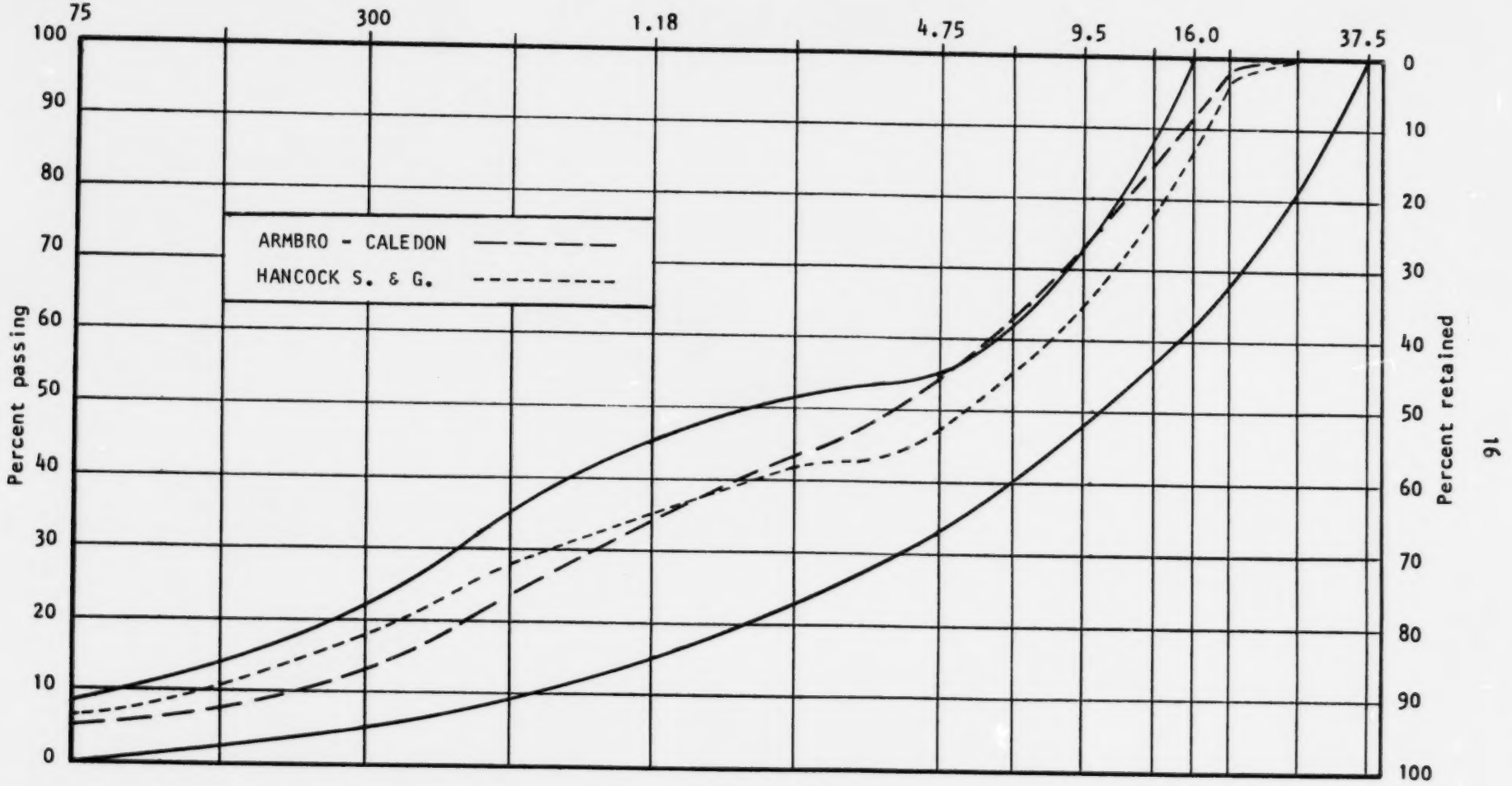

Figure 2. Crushed gravel materials.

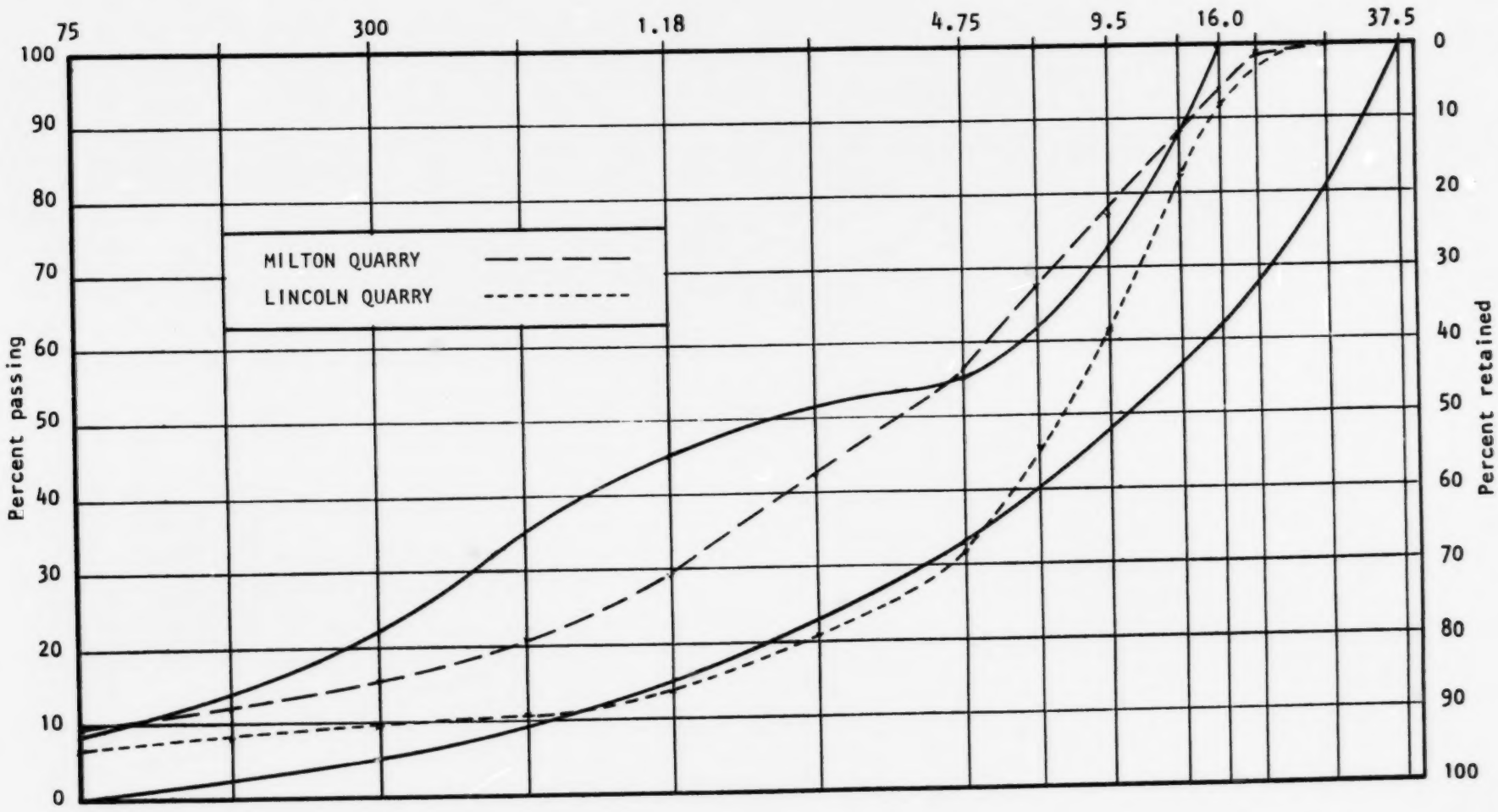

Figure 3. Quarried materials.

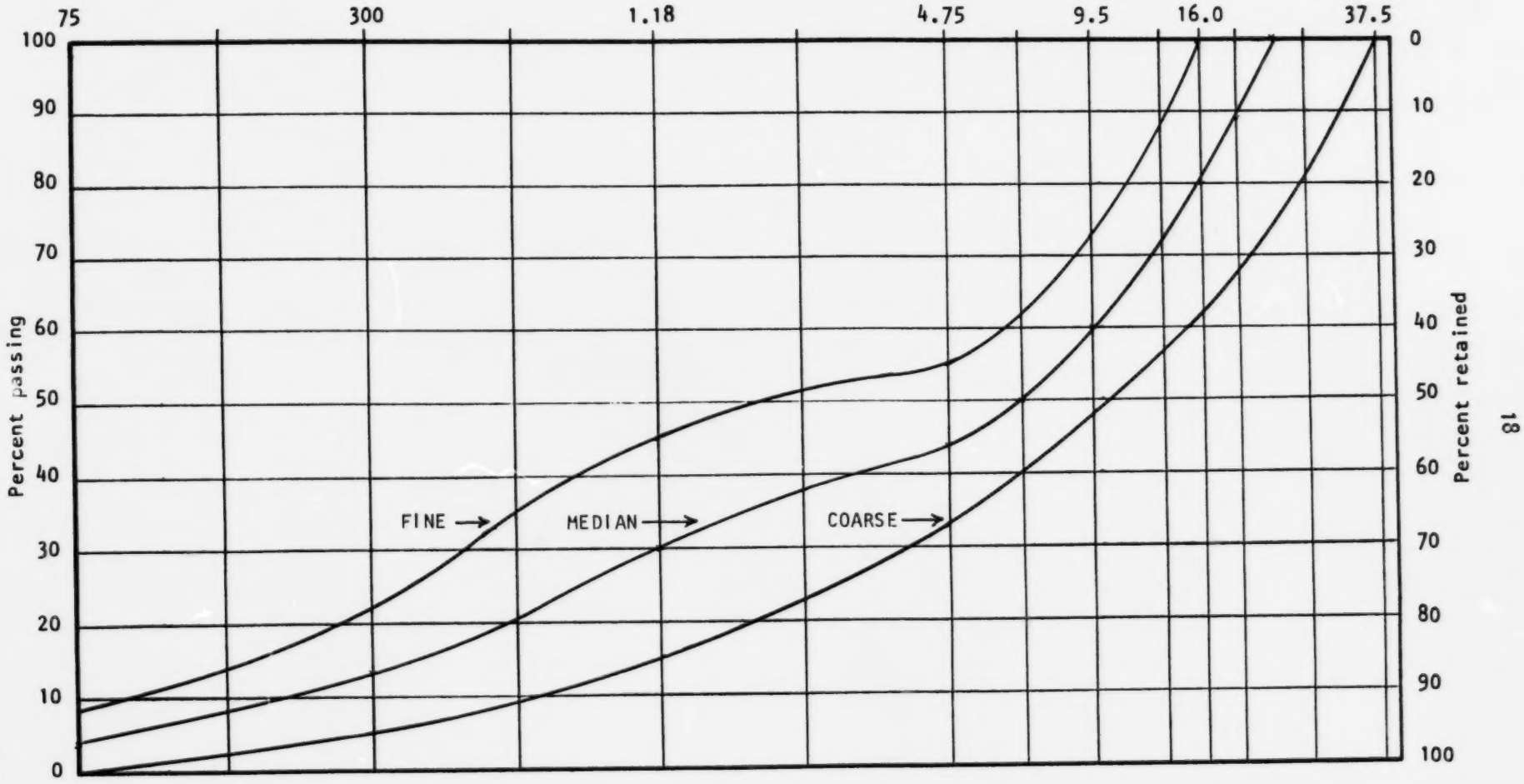

Figure 4. Test specimen gradations.

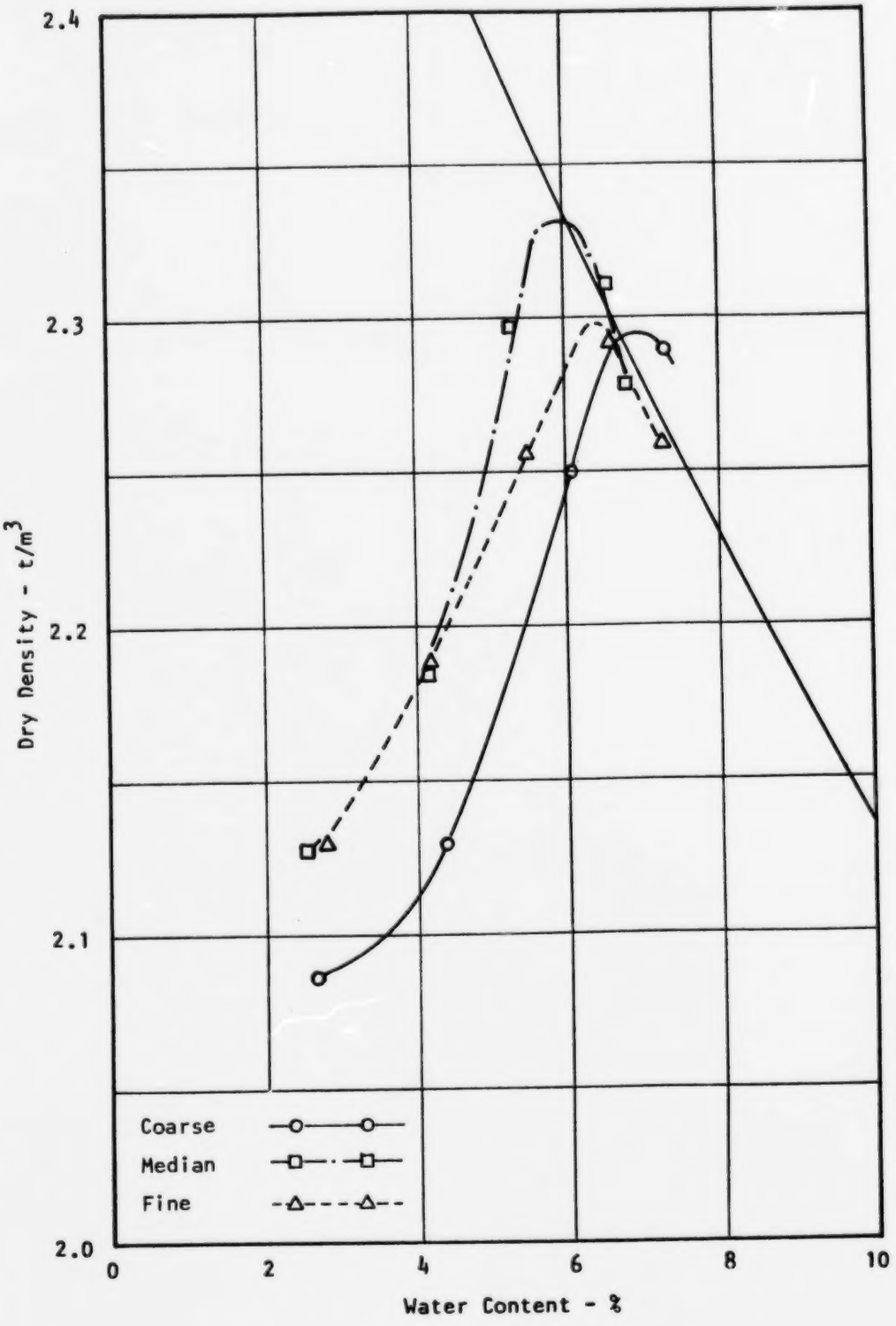

Figure 5. Armbro-Caledon material.
Unsealed mold.

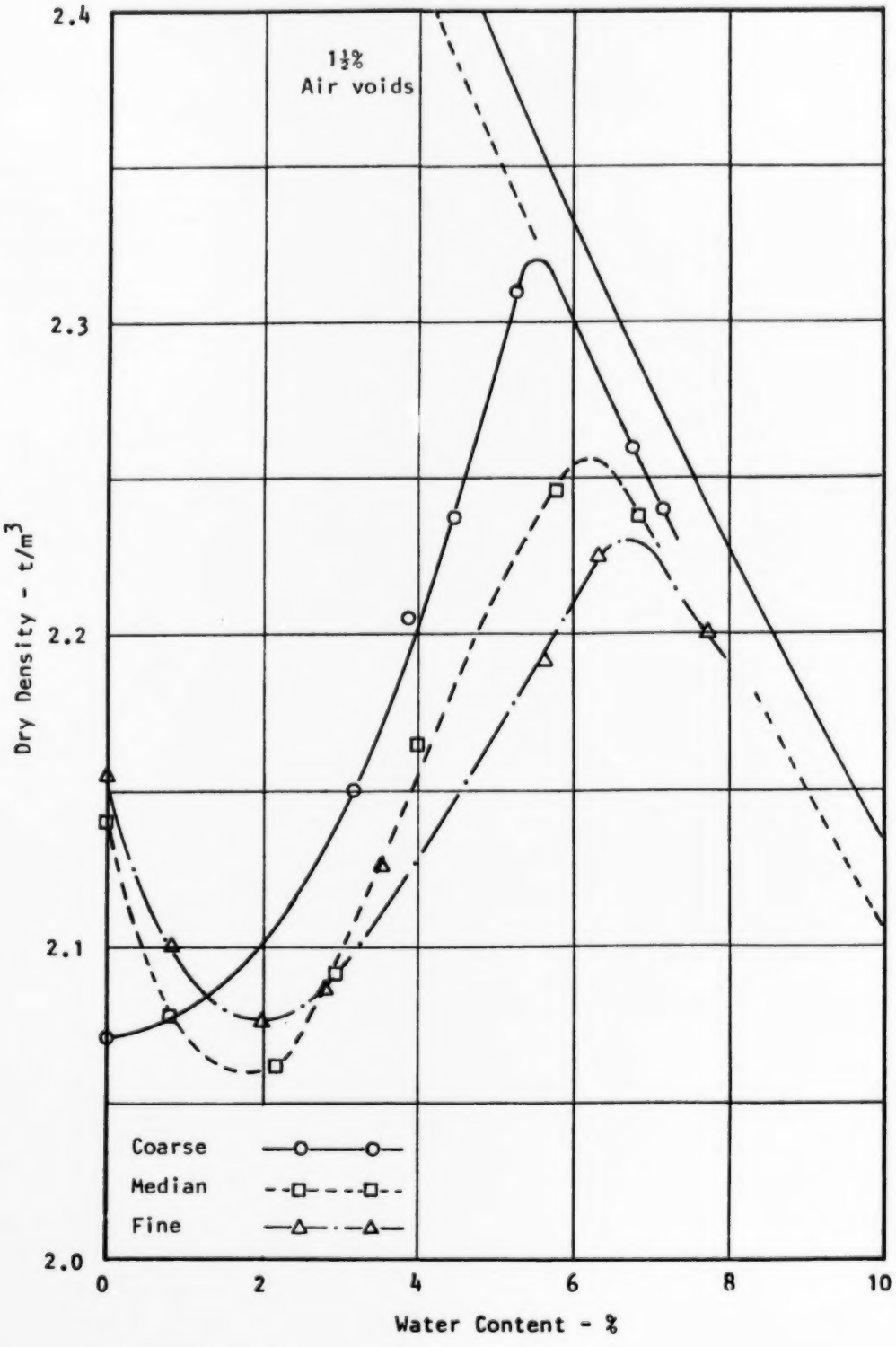

Figure 6. Armbro-Caledon material.
Sealed mold.

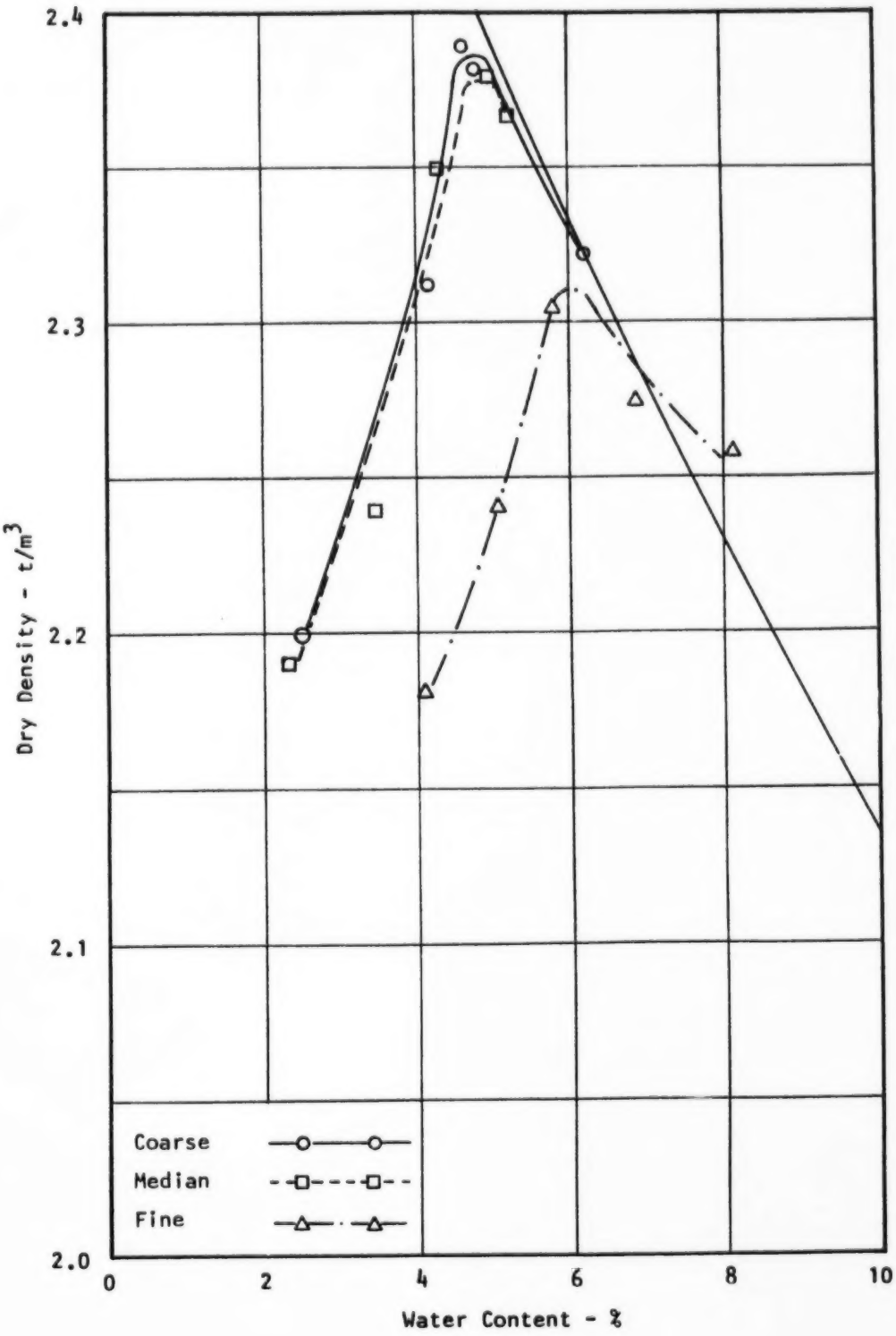

Figure 7. Hancock S. & G. material.
Unsealed mold.

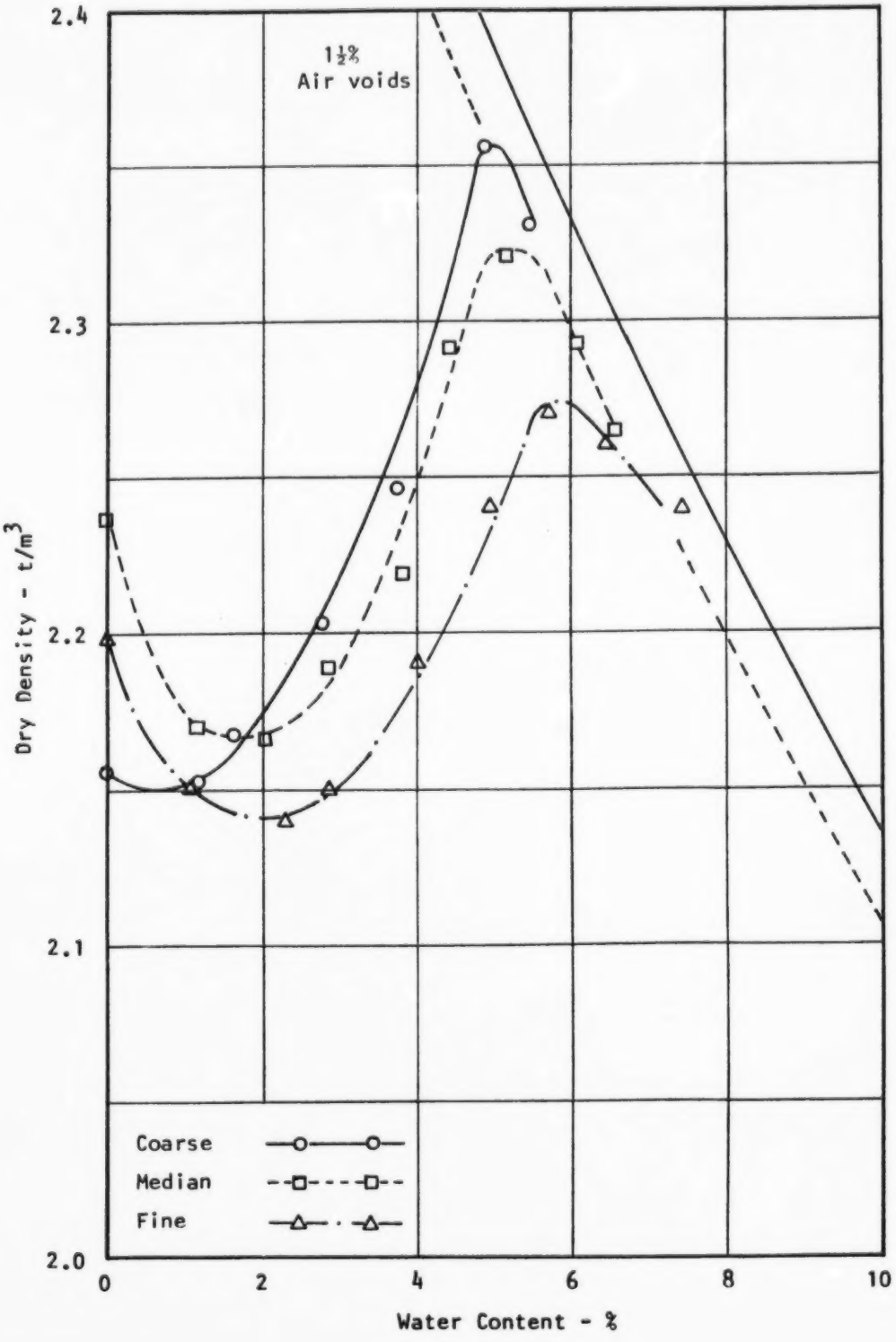

Figure 8. Hancock S. & G. material.
Sealed mold.

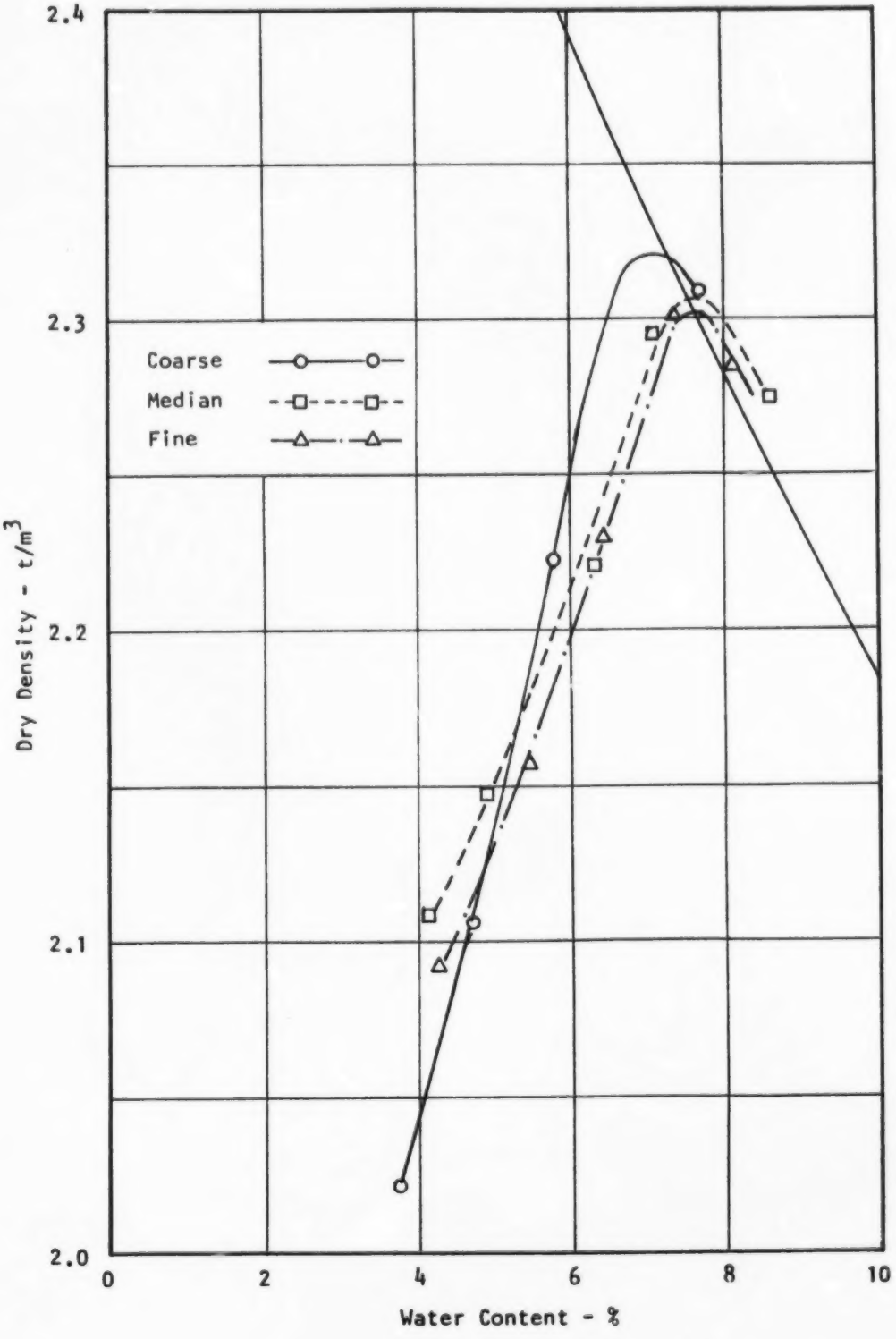

Figure 9. Milton Quarry material.
Unsealed mold.

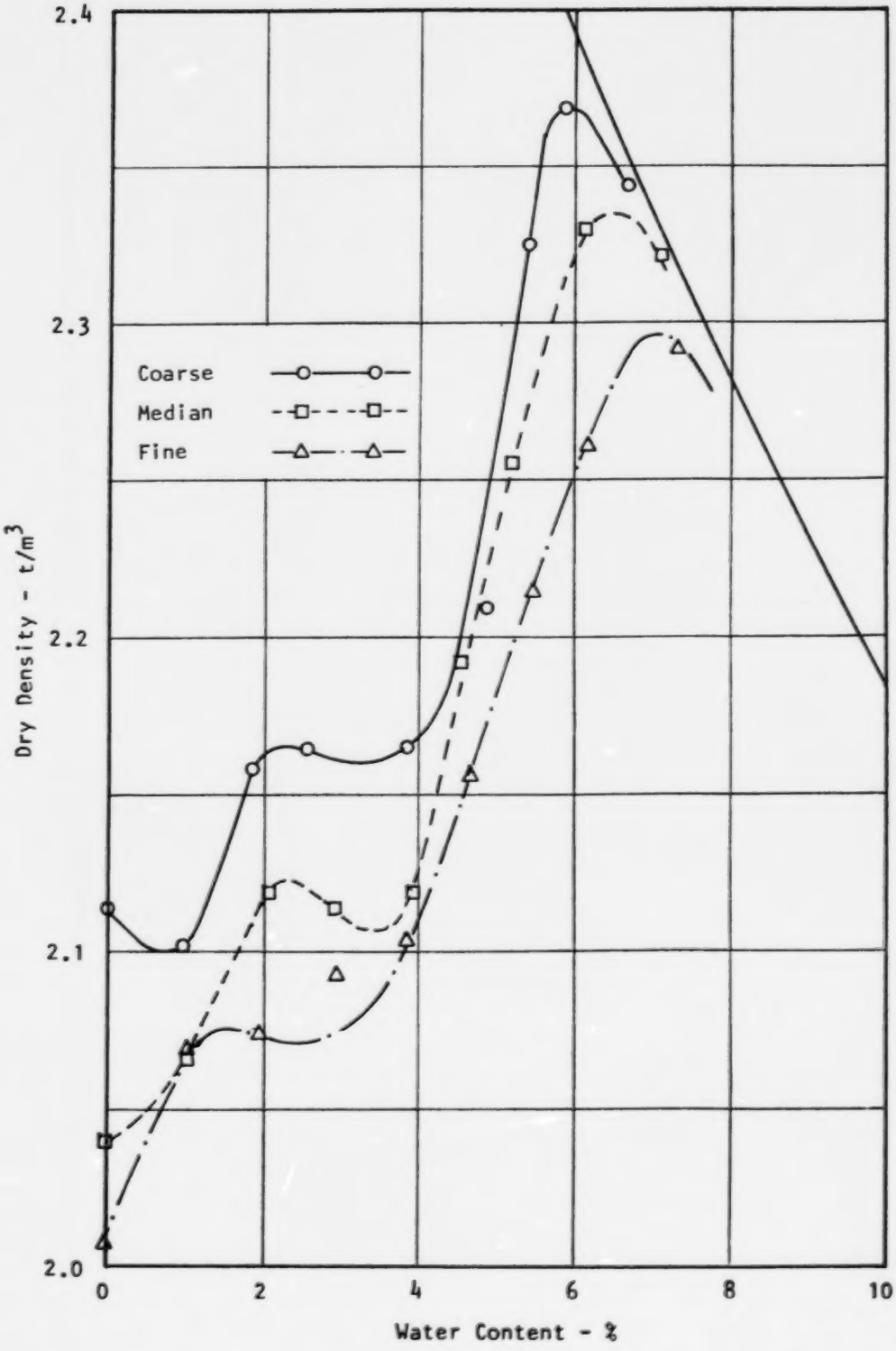

Figure 10. Milton Quarry material.
Sealed mold.

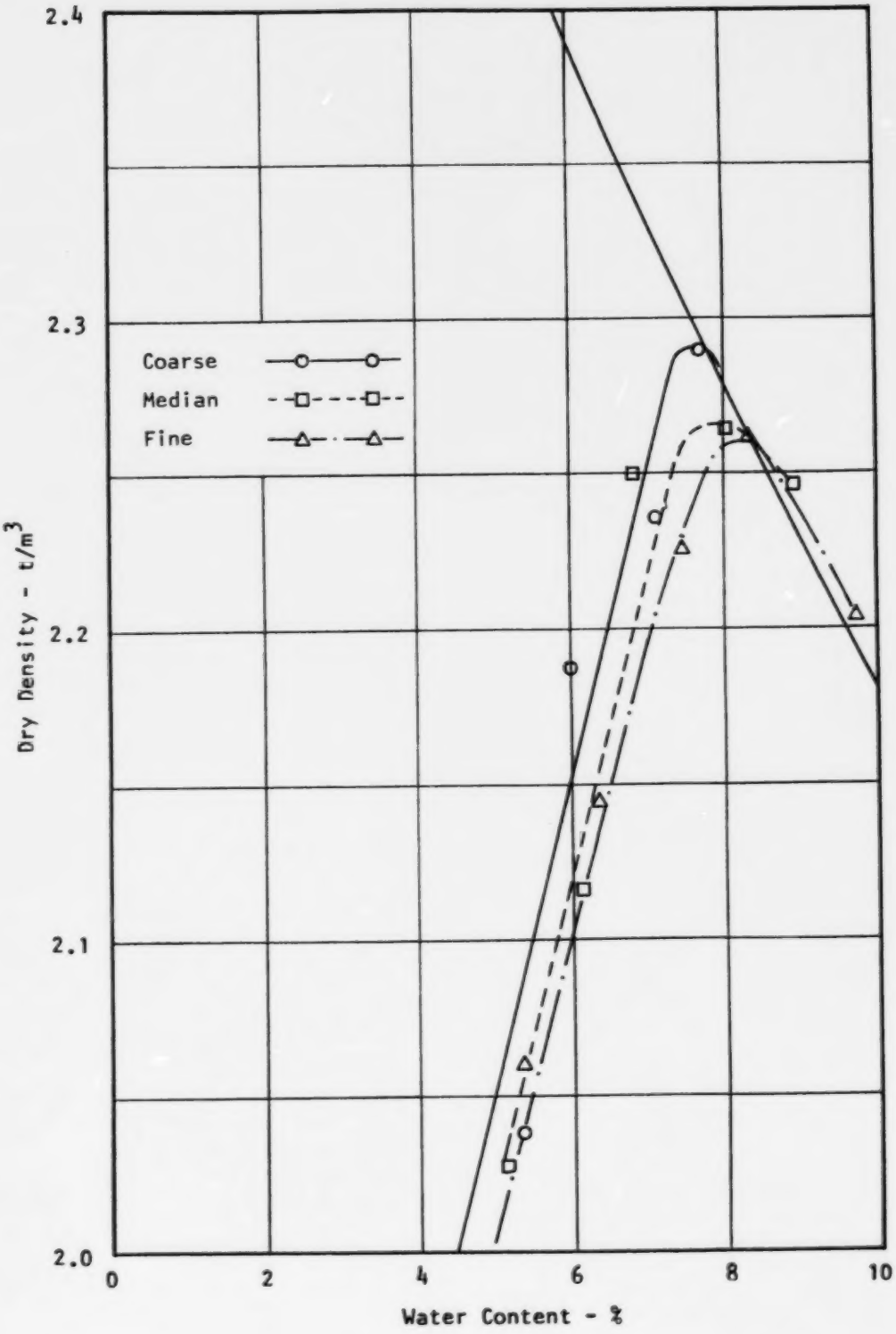

Figure 11. Lincoln Quarry material.
Unsealed mold.

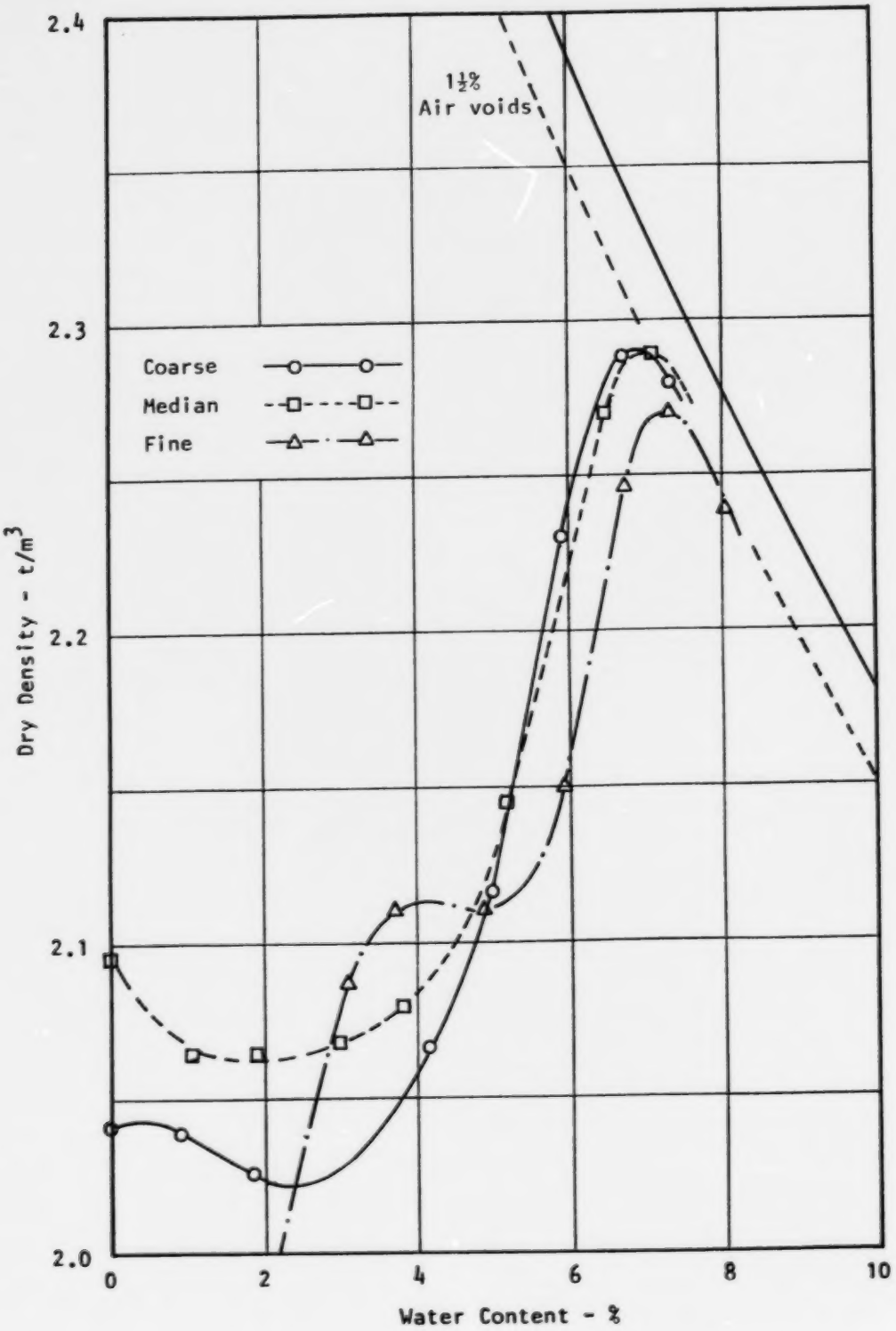

Figure 12. Lincoln Quarry material.
Sealed mold.

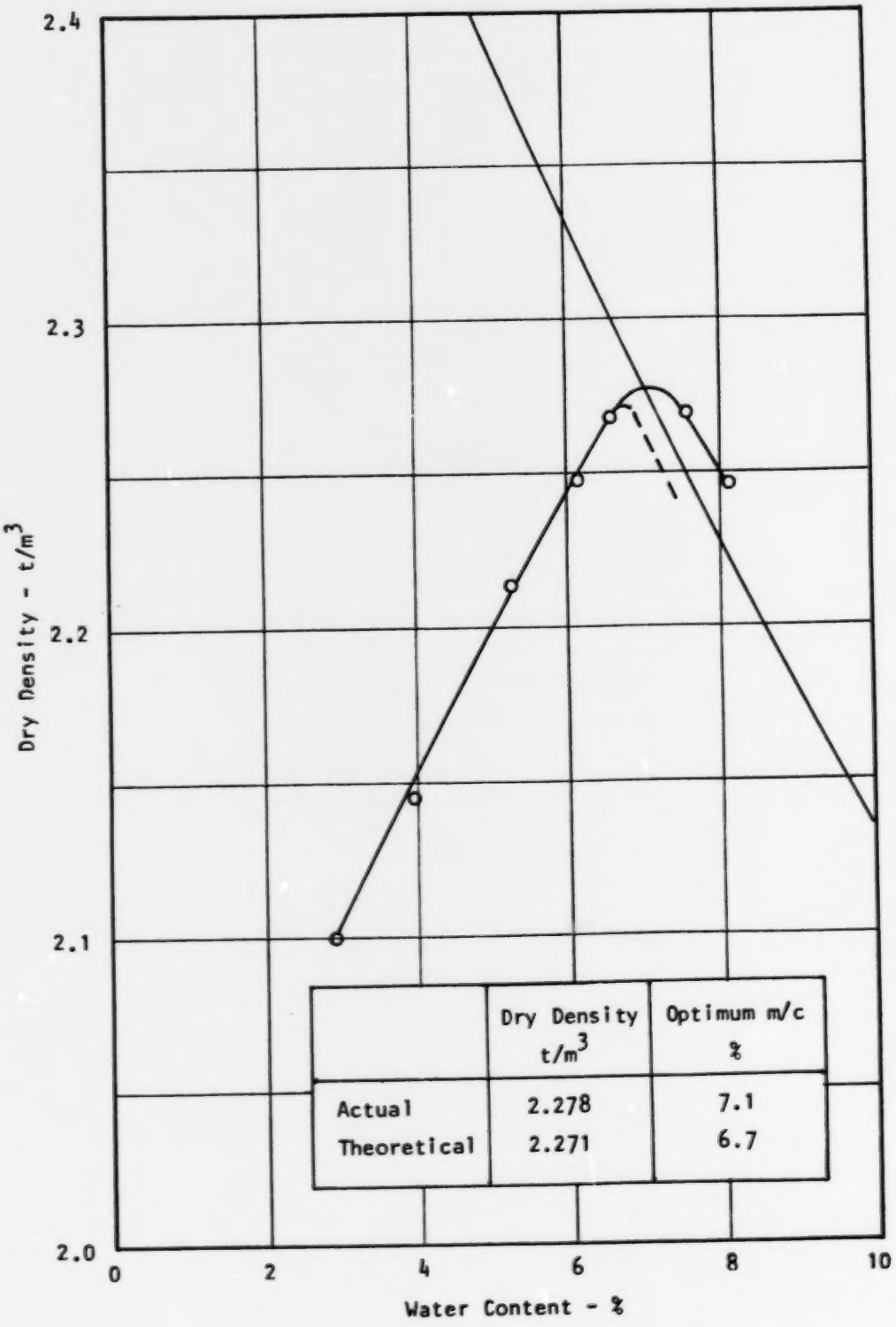

Figure 13. Construction of theoretical Optimum Moisture Content point.

APPENDIX 2

TABLE 5

D_R	WATER CONTENT %								
	4	5	6	7	8	9	10	11	12
2.68	2.420	2.364	2.309	2.257	2.208	2.160	2.114	2.070	2.028
	151.1	147.5	144.1	140.9	137.7	134.8	131.9	129.2	126.6
2.70	2.437	2.379	2.323	2.271	2.220	2.172	2.126	2.082	2.039
	152.0	148.4	145.0	141.7	138.5	135.5	132.7	129.9	127.2
2.72	2.453	2.395	2.339	2.285	2.234	2.185	2.139	2.094	2.051
	153.1	149.4	145.9	142.6	139.4	136.4	133.4	130.7	128.0
2.74	2.469	2.439	2.353	2.299	2.247	2.198	2.151	2.105	2.062
	154.1	150.4	146.8	143.4	140.2	137.1	134.2	131.4	128.7
2.76	2.486	2.425	2.368	2.313	2.261	2.211	2.163	2.117	2.073
	155.1	151.3	147.8	144.3	141.1	138.0	135.0	132.1	129.4
2.78	2.502	2.441	2.383	2.327	2.274	2.224	2.175	2.129	2.085
	156.1	152.3	148.7	145.2	141.9	138.8	135.7	132.9	130.1
2.80	2.518	2.456	2.398	2.341	2.288	2.237	2.188	2.141	2.096
	157.1	153.3	149.6	146.1	142.8	139.6	136.5	133.6	130.8

Table 2. Dry density values used to construct zero air voids line (t/m^3 and p.c.f.).

APPENDIX III

EFFECT ON ONE-POINT PROCTOR DETERMINATIONS

When the draft of this report was being reviewed a question was raised as to the effect of the findings on data presented in Report EM-54 'One Point Proctor Determination of Moisture-Density Relationship using a Family of Curves'.

This was investigated by referring to Figure 3 of Report EM-54 and using the data referring to all Regions except Northwestern. It is to be expected that materials producing dry densities in the order of 2.4 t/m^3 and higher would have relative densities approaching the order of 3.0. Accordingly, five curves were selected at random from the figure referred to and zero air void lines constructed for values of relative density of 2.7, 2.8, 2.9 and 3.0. This data is presented in Figure 14, Page 32.

It may be seen that there is a reasonable relationship between the curves selected and the zero air void lines constructed.

Therefore, it is reasonable to assume that the data presented in Report EM-54 is sufficiently accurate for the intended use.

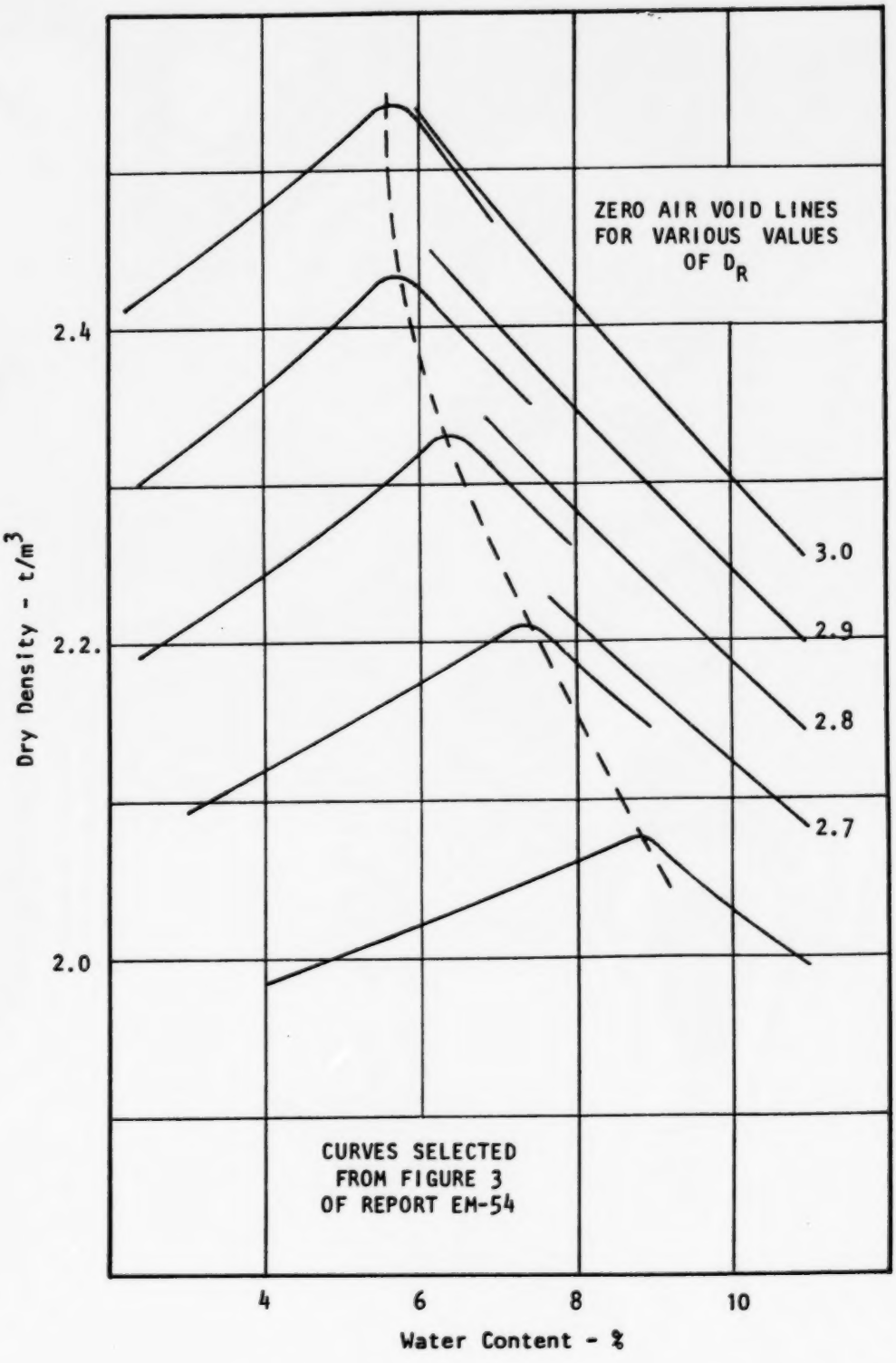

Figure 14. One Point Proctor Curves.